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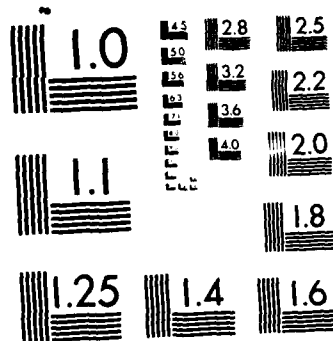
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## ACOUSTIC FORECAST FOR SHUTTLE LAUNCHES AT VANDENBERG AFB

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### Abstract

Acoustic loads on ground support structures for Shuttle Launches at Vandenberg Air Force Base are forecast in a way that satisfies local reverberations. Acoustic spectra at points neighboring the Vandenberg Launch Mount are expected to be enhanced by as much as 15 db by site specific acoustics. Simulated launch loads on the east face of the Payload Preparation Room have a maximum overall sound power level of 156 db. The corresponding sound power maximum for the same averaging time, bandwidth and distance at Kennedy Space Center over a path free of reverberations and ground water cloud attenuation is 149 db. The peak pressure on the Payload Preparation Room after 10 launches is predicted to be 165 db. After a lifetime of 100 launches, peak pressure on the facility is expected to reach 167 db.

### Nomenclature

a	Reference distance
c	Phase velocity
c	Speed of sound in air
e	2.71828
E(a,t)	Empirical envelope term
F( $\beta_{STS}$ )	Peak Pressure Probability
k	Wave number
M(t)	Operator that connects the Shuttle and explosion
N(0,1)	Standard, independent, normal process
p'	Spherical wave
P <sub>b</sub>	Boundary pressure
P <sub>N</sub>	Peak pressure after N launches
P <sub>s</sub>	Source pressure
P <sub>STS</sub>	Boundary pressure for a Shuttle launch
P <sub>STS</sub>	Peak boundary pressure for a launch
P <sub>x</sub>	Boundary pressure generated by an explosion
r	Source distance
t	Time
$\delta(t)$	Dirac delta function
X(a,t)	Explosion source wavelet
Y(t)	Shaping operator corresponding to Shuttle pressure spectrum
*	Convolution
$\omega$	Angular frequency
$\Theta$	Boundary modifier

### I Introduction

This report covers one element of a comprehensive effort to forecast and measure the vibro-acoustic environment for Shuttle launches at Vandenberg Air Force Base (VAFB) in support of facility design, operation and lifetime prediction.

### II Overview

The launch complex and natural setting for Shuttle operations at Kennedy Space Center (KSC) and Vandenberg differ markedly in many ways. This paper deals with expected differences in Shuttle generated loads 200 to 400 meters from the Launch Mount (LM) caused by differences in site boundary conditions. At these distances KSC launch generated acoustics are well described by purely outward propagating, spherical waves impinging on a flat, dense earth; multipathing and backscattering are minimal once the Shuttle clears the pad. In contrast, multipathing and backscattering will be important factors for determining the magnitude, phase and frequency content of acoustic loads on ground support structures at VAFB. The magnitude, phase and frequency of the applied load are well recognized input parameters for determining building motion.

Pressure simulations given here cascade operators that satisfy Shuttle source acoustics with responses peculiar to KSC and VAFB. Pressure simulations for Vandenberg launches satisfy reverberations excited by test shots located over the Launch Mount with all major structures in launch configuration. The forecast largely ignores dynamic pressure, ground cloud and launch mount attenuation terms in favor of the peak load regime on structures 300 meters from the Launch Pad. Maximum loading on these structures occurs some 12 seconds after liftoff with the Shuttle at an altitude of 300 meters. In turn, the apparent source height for shuttle generated acoustics at this time and range is 200 meters, well below the Shuttle, imbedded the plume.

### III Mapping the Source Term

Surface pressure produced by an acoustic disturbance can be separated into an incident term and contributions arising from the boundary, i.e.

$$P_b(r,c,t) = [\Theta(r,c,t) + \delta(t)] * P_s(r,c,t)$$

For a perfectly reflecting dense, flat earth,  $\Theta(r,c,t) = \delta(t)$  and the surface pressure is just double the incident term. For a less than perfectly reflecting, but flat earth,  $\Theta$  need not be unity nor real. Indeed, for low velocity, soil covered areas,  $\Theta(r,c,t)$  typically gives rise to both homogeneous and inhomogeneous waves.

For a windless, uniform atmosphere  $p(r,c,t)$  propagates outward from a monopole as a spherical wave until impinging on a boundary. For an irregular surface such as encountered at VAFB, a profusion of acoustic paths can develop to connect the source with a field point. Dif-

ferences in pressure arise from differences in source, path or boundary properties. The forecasts developed here use site sensitive operators established by test shots to map a Shuttle source reference pressure into a site dependent surface pressure at launch time.

#### IV The STS Source

At KSC, Shuttle generated surface pressure at a field point can be represented by:

$$P_{STS}(a,t)=[\theta(a,c,t)+\delta(t)]*Y(t)*E(a,t)*N(0,1)$$

for repeated launches over the same trajectory. Extrapolations around the reference point, a, satisfy far field, spherical acoustics emitted from a source region imbedded in the plume, namely:

$$p'(r,t)=(a/r) p'(a,t)*\exp i[\omega t-k(a-r)].^7$$

with  $c=\omega/k$

In this representation,  $F(a,t)$  is a slowly varying envelope term that includes the effect of range and plume orientation on level. In turn,  $N(0,1)$  is a zero mean, independent, standard normal process. Maximum level surface pressures for Shuttle launches at KSC have the same first and second order statistics as  $[\theta(a,c,t)+\delta(t)]*Y(t)*N(0,1)$ . The value of the peak pressure for a sequence of launches is forecast by treating successive launches as independent events.

#### V The Explosive Source

For an atmospheric explosion over a path with the same boundary values and offset as the launch, surface pressure is given by:

$$p_x(a,t)=[\theta(a,c,t)+\delta(t)]*X(a,t).^7$$

As for the rocket, the surface pressure excited by an explosion over a flat, dense, earth is readily extrapolated locally around  $r=a$  as spherical acoustics with  $\theta=2*\delta(t)$  for all but an aircoupled term.

Figure 1 is a standard spectrum for a Shuttle launch and explosion for a common range and averaging time over a flat, unobstructed site. The two spectra are similar in shape. The location of the spectral maximum in each case is largely established by source strength. The operator needed to map the pressure spectrum produced by a 2.5lb. charge into a shuttle spectrum is low pass with a corner frequency somewhat less than 5 Hz. The operator defined by  $M(t)=Y(t)*X^{-1}(t)$  describes acoustics emitted by the undeflected plume in terms of an explosive source, independent of site boundaries. Pressure simulations shortly after the Shuttle clears the pad are formed by measuring explosion wavelets

over a common path of interest and computing:

$$P_{STS}(a,t)=p_x(a,t)*M(t)*E(a,t)*N(0,1)$$

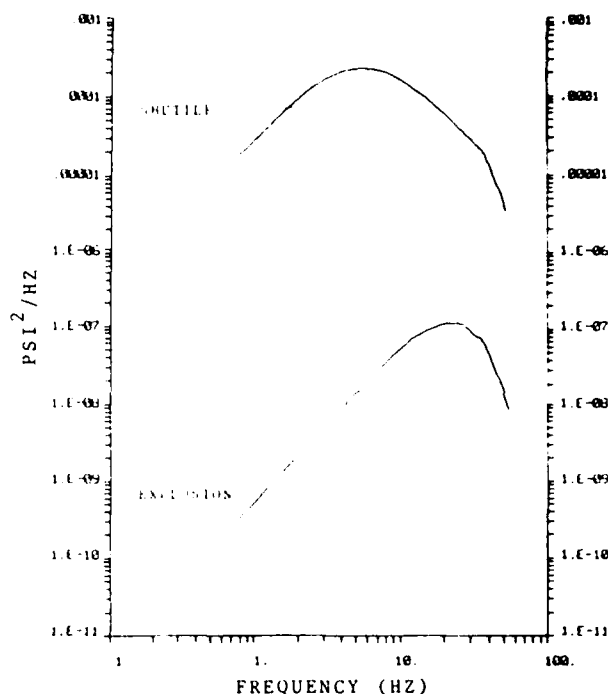


Fig.1 Shuttle and explosion spectra for a flat, unobstructed area.

Figure 2 is a simulated surface pressure for a Shuttle launch at a flat, uncluttered site based on explosion wavelets. Directly below the simulation is the surface pressure observed at KSC for Mission 41B. The simulation closely mimics the real launch surface pressure, spacially and temporally, during the peak pressure regime.

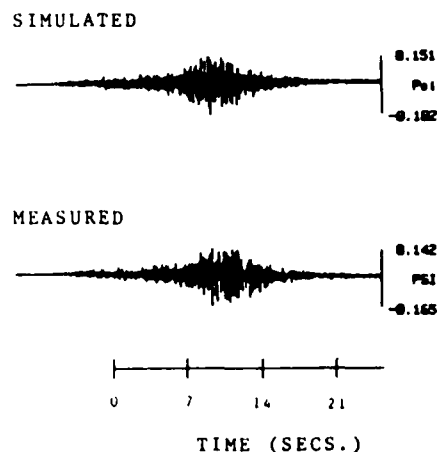


Fig.2 Simulated and measured surface pressure for a Shuttle launch.

## VI Explosive Wavelets at VAFB

Figure 3 contrasts the pressure wavelet produced by a VAFB test shot for a station on the east face of the Payload Preparation Room (PPR) with the wavelet obtained at a flat earth site for the same offset and charge size. The wavelet measured at the flat earth site is short lived. It propagates outward without a change in shape while spreading as  $1/r$ , the two characteristics of a spherical wave. In contrast, the same source wavelet at VAFB is enhanced by reflections. Also, it has an extended duration. Reverberations following the main pulse do little to alter the Overall Sound Power Level (OASPL). They do, however, materially alter the wavelet's spectrum.

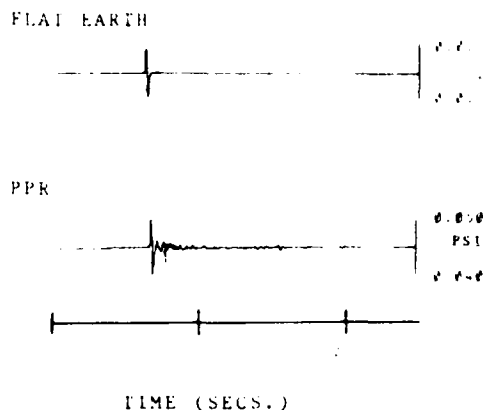


Fig. 3 Explosion pressure wavelets at a common offset.

Figure 4 is the ratio of the pressure spectrum at this station with one obtained at a flat site, all else being equal. The spectrum for the east face of the PPR is as much as 15db greater than that at a flat, open site because of differences in boundary terms. The impact of this change in load on building vibration depends on the dynamics of the structure in question. If the frequency and phasing of the enhanced load align with important building responses, the impact will be large. If not, the effect might well be trivial. The results do call for exercising caution when extrapolating vibro-acoustic data obtained at KSC over to VAFB even when no substantial change is expected in the OASPL.

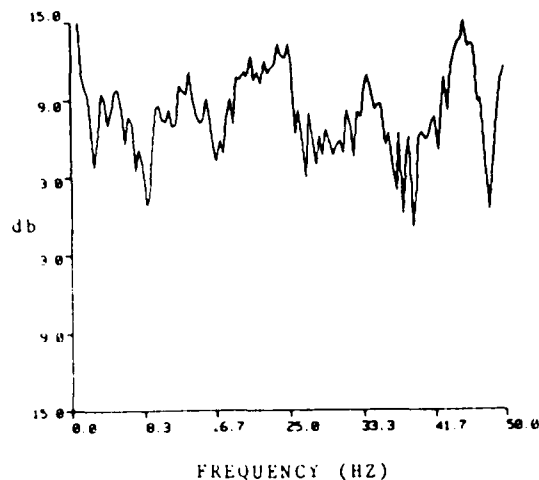


Fig. 4 Spectral ratios for Vandenberg

## VII Shuttle Launch Pressure Simulations

Figure 5 is a set of simulated launch pressures based on small test shots detonated over the Launch Mount. The explosions in these tests are limited to a maximum elevation of 60 meters. Hence, the simulation best applies to the interval leading up to the time of peak loading. Indeed, the relative error might become large once the Shuttle gets higher and south of the site.

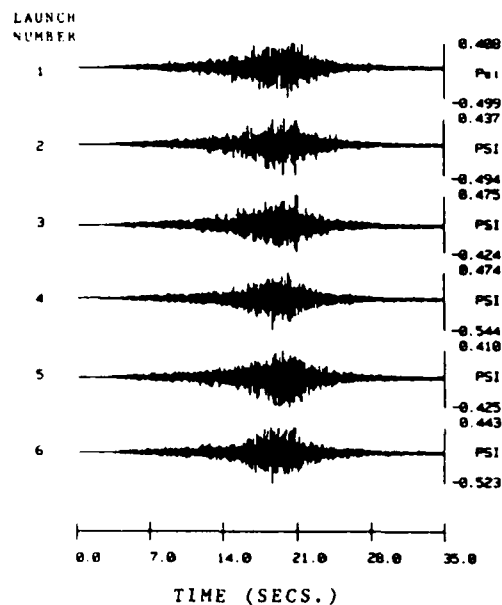


Fig. 5 Simulated launch pressure for the East face of the PPR.

Figure 6 is simulated launch pressure for a station on the roof of the Administration Building (AB). The AB is a fixed, multistoried structure that abuts the south wall of the PPR. As for the PPR, the AB roof pressure spectrum is a significantly altered version of what is expected for a flat site. Once again, pressure simulations 10 seconds or more after liftoff are likely to be in error, for as the Shuttle climbs higher and south of the Launch Mount, reflections off the PPR will begin to phase align and add to the incident term to enhance the roof load. It is believed that these constructive reflections will develop too late to alter the peak load value.

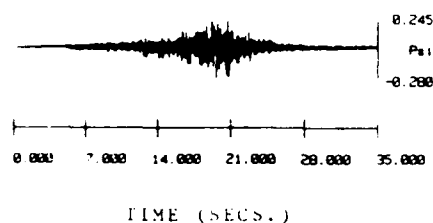


Fig. 6 Simulated launch pressure for the roof of the AB.

#### VIII The Forecasting Method

The credibility of forecasting plume generated acoustics from explosions has been demonstrated in part by predicting pressures produced by static firing an F100 engine in a Hush House. Figure 7 shows the pressure wavelet produced by a small charge exploded near a Hush House at Luke AFB. As at Vandenberg, the explosion wavelet at the location of interest is altered by reverberations.

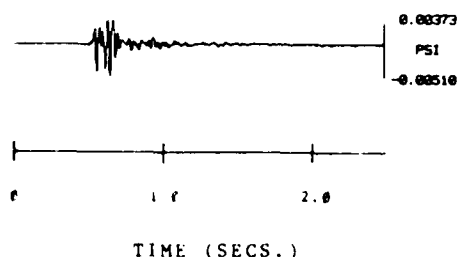


Fig. 7 Explosion wavelet for Luke AFB.

Figure 8 is the pressure for a F100 engine operating in the Hush House that satisfies the propagation characteristic of the site established by the explosion. Just below the fore-

cast is the actual pressure measured during the run. The forecast is quite accurate. The mismatch that does exist is readily explained by a difference in the location of the Hush House and the explosion. Launch simulations for the Shuttle expended considerable effort to collocate the explosion and rocket sources. VAFB forecasts should be free from this error, except where explicitly noted.

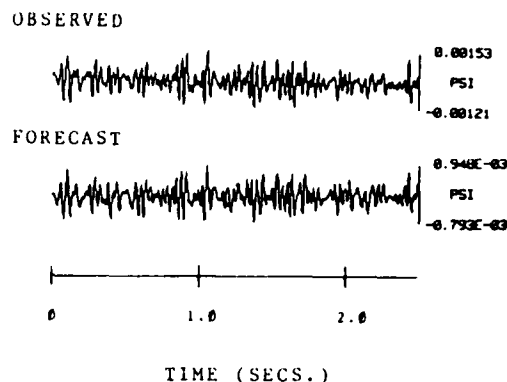


Fig. 8 Hush House pressure for Luke AFB.

#### IX Peak Pressure Estimates

Shuttle launch pressure for a fixed observer is represented by a nonstationary, dependent, random process. The expected absolute peak pressure experienced by a ground facility over time is a quantity that can only increase (or possibly remain the same) after each launch. The absolute peak pressure expected after a prescribed number of launches is based on the best fitting asymptotic probability of largest values obtained in simulation. The cumulative frequency of largest pressures,  $F(\hat{p}_{STS})$ , for a sequence of independent, simulated launches is plotted in the form,  $Y = \ln[\ln F(\hat{p}_{STS})]$ , Figure 9. The modified  $F(\hat{p}_{STS})$  values are taken to satisfy the linear relation,  $Y = A \cdot (\hat{p}_{STS}^U - U)$  with a zero intercept,  $U = .44$  and slope  $A = 23$ . In this treatment the probability value  $F(\hat{p}_{STS}^U) = 1/e$  defines  $U$ . The approach taken here appeals to the fact that an exponential asymptotic probability leads to a linear relation between  $Y$  and  $\hat{p}_{STS}$ . The test for selecting the exponential distribution then becomes one of accepting or rejecting if the plotted values fall along a straight line. The linear relation shown in Figure 9 establishes the parameters needed to forecast the largest pressure after  $N$  independent launches by  $P_N = U + (\ln N)/A$ . The estimated absolute maximum of  $N$  launch pressure maxima for the east face of the PPR for a lifetime of 100 launches is 167db. The corresponding value for the AB roof is down by 6db.

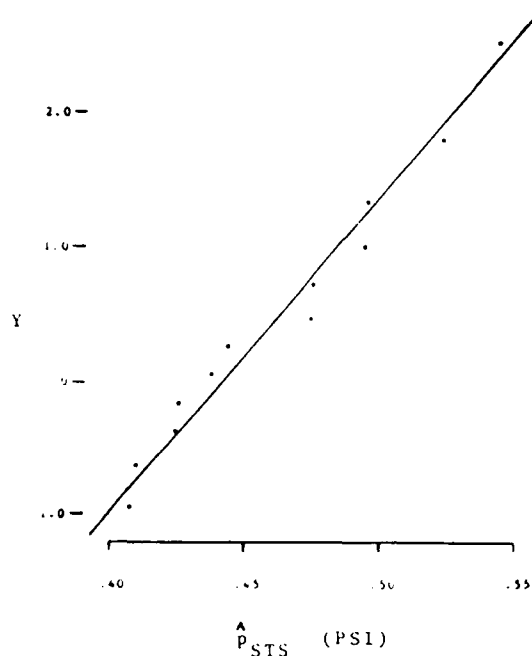


Fig.9 Absolute peak pressure forecast.

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